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Cropping system influences on soil physical properties in the Great Plains

J.L. Pikul, Jr[1,*], R.C. Schwartz[2], J.G. Benjamin[3], R.L. Baumhardt[2], and S. Merrill[4]

[1]USDA-ARS, 2923 Medary Ave. Brookings, SD 57006, USA.
[2]USDA-ARS, PO Drawer 10, Bushland, TX 79012, USA.
[3]USDA-ARS, 40335 County Road GG, Akron, CO 80720, USA.
[4]USDA-ARS, PO Box 459, Mandan, ND 58554-0459, USA.
*Corresponding author: jpikul@ngirl.ars.usda.gov

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Abstract

Agricultural systems produce both detrimental and beneficial effects on soil quality (SQ). We compared soil physical properties of long-term conventional (CON) and alternative (ALT) cropping systems near Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan (ND); Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. Objectives were to quantify the changes in soil physical attributes in cropping systems and assess the potential of individual soil attributes as sensitive indicators of change in SQ. Soil samples were collected three times per year from each treatment at each site for one rotation cycle (4 years at Brookings and Mead). Water infiltration rates were measured. Soil bulk density (BD) and gravimetric water were measured at 0–7.5, 7.5–15, and 15–30 cm depth increments and water-filled pore space ratio (WFPS) was calculated. At six locations, a rotary sieve was used to separate soil (top 5 cm) into six aggregate size groups and calculate mean weight diameter (MWD) of dry aggregates. Under the CON system at Brookings, dry aggregates (>19 mm) abraded into the smallest size class (<0.4 mm) on sieving. In contrast, the large aggregates from the ALT system abraded into size classes between 2 and 6 mm. Dry aggregate size distribution (DASD) shows promise as an indicator of SQ related to susceptibility of soil to wind erosion. Aggregates from CON were least stable in water. Soil C was greater under ALT than CON for both Brookings and Mead. At other locations, MWD of aggregates under continuous crop or no tillage (ALT systems) was greater than MWD under CON. There was no crop system effect on water infiltration rates for locations having the same tillage within cropping system. Tillage resulted in increased, decreased, or unchanged near-surface BD. Because there was significant temporal variation in water infiltration, MWD, and BD, conclusions based on a single point-in-time observation should be avoided. Elevated WFPS at Fargo, Brookings, and Mead may have resulted in anaerobic soil conditions during a portion of the year. Repeated measurements of WFPS or DASD revealed important temporal characteristics of SQ that could be used to judge soil condition as affected by management.

Key words: soil bulk density, dry aggregate stability, rotary sieve, aggregate size distribution, water infiltration rate, water filled pore space, soil organic carbon

Introduction

Considerable research has been conducted on relationships among cropping sequence, soil organic matter (SOM), and various biological and physical soil properties. It is generally accepted that crop production alone has caused a decline in SOM throughout the Great Plains[1,2]. Wheat–fallow crop sequence, being a common agricultural practice, has been implicated as the cause of serious declines in SOM[2–4].

SOM is linked to fertility and desirable soil tilth. Boyle et al.[5], in a review of the influence of SOM on soil aggregation and water infiltration, concluded SOM had a disproportionate effect on soil physical behavior. Hudson[6] reported that soils high in SOM have greater available water-holding capacity than soils of similar texture with less SOM. Bauer and Black[7] found that available water

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capacity remained constant in sandy soils across a range of soil C. However, in medium and fine-textured soil, available water capacity decreased with increasing soil C. Soane[8] reported that soil compaction was sensitive to small changes in SOM and, generally, decreased with increasing SOM. Maintenance of SOM seems to be a key to sustaining the soil resource and crop productivity[9].

The relationship of SOM to soil physical behavior is not always clearly defined. Degens[10] provides a review on the function of labile organic bonding and binding agents related to soil aggregation. Degens[10] suggests that conclusions on soil stabilization resulting from controlled incubation studies contribute little to understanding biological processes under field conditions. Soil organic carbon (SOC) accounted for about 70–90% of the variability in soil aggregate stability of a clay loam soil[11]. Bruce et al.[12] determined that increased phytomass input to a loamy sand increased aggregate stability and water infiltration. On a silt loam, Pikul et al.[13] found a significant correlation of BD and SOC with penetration resistance within the tillage layer. On long-term tillage, residue management, and N-fertility plots, Pikul and Zuzel[14] reported that SOM had a significant effect on porosity of surface crusts. Mulla et al.[15] attempted to quantify differences in aggregate stability between 'conventional (CON)' and 'alternative (ALT)' farms. They were not able to establish a relation between SOM and physical behavior of a Naff silt loam, although surface crusting was observed on the 'CON' but not on the 'ALT' farm.

A clear statement cannot always be made concerning the effect of tillage on runoff and infiltration even though tillage has been shown to affect SOM. Jones et al.[16] found that tillage increased infiltration rates and decreased runoff as compared with no tillage. They attributed these results to surface crusting of no tillage plots. Although tillage decreased runoff, it also increased water erosion of soil. Pikul and Aase[17] found subsoil tillage initially improved water infiltration, but the benefit was short-lived when followed by secondary tillage. Seta et al.[18] found that reduced tillage reduced runoff and sediment loss from 0.01-ha runoff plots subjected to simulated rainfall. At the watershed scale, Edwards et al.[19] could not confidently evaluate the erosion-controlling benefits of no-tillage in a corn–soybean rotation because of great year-to-year variability in measured erosion. Increased water transmission in no-till soil has been attributed to surface-connected macropore channels[20].

Variable relations between tillage and soil BD have also been observed. Investigators have reported greater BD can be expected with no-tillage as compared with CON tillage practices[21–23]. There are reports that tillage has had an insignificant effect on BD[24,25]. Mielke et al.[26] found that fallow tillage did not affect BD in a silt loam soil; however, reduced tillage decreased soil BD in a loam soil. Interpretation of BD measurements can be difficult because large sampling increments may overlap layers of compacted and non-compacted soil and dilute or mask treatment effects. Investigators using thin sampling increments of 0.02 m have successfully identified unique profiles of SOC and BD in long-term tillage and residue management experiments[13,27,28].

The state of the soil physical environment is important for maintaining sustained agronomic production; a concept embodied in the presumption that good soil tilth is a precursor to high crop productivity. Agricultural systems may produce both detrimental and beneficial effects on soil physical condition. Soil compaction frequently occurs when agricultural equipment passes over a field, but little is known about the long-term interaction of crop systems, residue, and fertilizer management on soil physical condition.

A multi-location study was conducted during 1999–2002 at eight Great Plains locations to evaluate a number of physical, chemical, and biological properties associated with SQ. Objectives were to quantify changes in soil physical attributes in cropping systems and assess the potential of individual soil attributes as sensitive indicators of changes in SQ.

Materials and Methods

Contrasting management treatments within eight long-term cropping system studies were compared (Table 1). Treatments selected at each site differed in management intensity, as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity. The Akron, Fargo, and Mandan locations included a tillage variable as well as a cropping intensity and crop species variable in the cropping system. Locations that had the same tillage system but different cropping intensity or crop species in the cropping system were Brookings, Bushland, Mead, Sidney, and Swift Current. Varvel et al.[29] describe these long-term field experiments and standard soil sampling procedure used at each site.

Briefly, soil BD and gravimetric water content (GW)[30] were determined concurrently from core samples taken at 0–7.5, 7.5–15, and 15–30 cm depth increments[31]. Soil samples were collected from the same plots for the duration of one crop rotation cycle. Samples were collected prior to planting, once during the growing season and immediately after harvest. For each depth increment, density and water content relations[32] were used to calculate water-filled pore space ratio (WFPS). Volumetric water (VW) was calculated as:

$$VW = GW \times BD$$

Soil porosity (SP) was calculated as:

$$SP = 1 - BD/2.65$$

where a constant of $2.65\,g\,cm^{-3}$ was used to estimate particle density. WFPS was calculated as:

$$WFPS = VW/SP$$

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/Soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2 ×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2 ×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied = N fertilizer application rate based on soil test results.
[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

About 7 kg of surface soil (0–5 cm) was randomly (approximately six locations per plot) collected on each plot with a shovel in order to measure dry aggregate size distribution (DASD). Measurements were taken at Brookings and Mead for 3 years, at Bushland, Fargo, and Mandan for 2 years, at Swift Current for only 1 year, and none were taken at Akron and Sidney. After air drying, aggregate size distribution was determined by using a rotary sieve[33]. Mean weight diameters (MWDs)[34] were calculated based on the mass fraction of dry aggregates in six size groups. Group 1 was soil < 0.4 mm, group 2 was 0.4–0.8 mm, group 3 was 0.8–2 mm, group 4 was 2–6 mm, group 5 was 6–19 mm, and group 6 was > 19 mm. Representative particle diameter for groups 2–5 was the arithmetic mean of upper and lower sieve diameters, 0.4 mm diameter for group 1, and 19 mm for group 6.

Soil aggregates obtained using the rotary sieve from the Brookings and Mead sites were further processed to measure dry aggregate stability, water stability, and SOC. The rotary sieve tends to abrade aggregates and a measure of this abrasion was determined by running individual aggregate groups through the sieve a second time. The second run provides an estimate of dry aggregate stability and is closely related to susceptibility of the soil to wind erosion[35]. Water stability was measured using a wet sieving device[36]. We measured water stability of dry aggregates to evaluate treatment effect on soil slaking. Soil organic C was determined by combustion using a LECO CN 2000 analyzer (LECO Corp., St Joseph, MI, USA).

Infiltration was measured at six locations on each plot using a single ring infiltrometer[36]. An aluminum infiltration ring, 15 cm diameter by 13 cm long, was inserted into the soil to a depth of 7.5 cm. A piece of plastic wrap was inserted into the ring with the edges of the plastic draping over the edges of the infiltration ring. Distilled water was added to the ring to correspond to a 25 mm depth in the ring. The plastic wrap was removed from the ring and the time required for the water to infiltrate into the soil was measured. After infiltration of the first 25 mm of water, a second volume of water (wet run) was added to the ring to correspond to a 25 mm depth in the ring. The purpose of the first volume of water was to remove the confounding effects of having different antecedent soil water contents at the time of each infiltration test. The time required for the second volume of water to infiltrate was measured and those measurements are reported here. Duplicate infiltration measurements were made within the row (for row crop systems), on trafficked interrow, and non-trafficked interrow.

Analysis of variance was applied to each soil property measured, to determine differences between treatments and sampling times within each location. Analysis of variance and statistical comparisons were completed using the PROC MIXED procedure of SAS[37] assuming a completely randomized block design at each location. Cropping system (treatment) and sampling time were designated as fixed effects and plot replicates nested within treatment was designated as a random effect. Probabilities of WFPS exceeding a critical soil-aeration-threshold (SAT) value were determined using parametric distribution analysis (MINITAB Statistical Software, State College, PA, USA).

Results and Discussion

Infiltration

Cropping system had a significant effect on infiltration for at least one position (Table 2) at the Akron, Fargo, and Mandan locations. All sites except Sidney had a significant time effect on infiltration. Measurements at the Sidney site were only in the row position so that possible differences induced by cropping system may have been negated by the planting operation.

Infiltration rates varied considerably among locations (Table 3). Rates varied from about 1 $cm\,h^{-1}$ at the Akron and Mandan locations for the track position to over 100 $cm\,h^{-1}$ at the Fargo location. Generally the track position had lower infiltration rates as compared to the no track or row positions.

A system-by-time interaction was significant at the Akron, Fargo, and Mandan locations, indicating that cropping system effects were not consistent throughout the duration of the experiment. At the Akron location, the CON system had a greater infiltration for the second sampling in 2000 at the no track position, but did not have a significant effect at any other time or position. At the Fargo location, the CON system had greater infiltration at the row and no track positions for the second sampling in 2000 but not at other times. At the Mandan location, there appeared to be a cyclic pattern to the infiltration rate for the ALT system where infiltration rate increased during the growing season and then decreased. The cyclic pattern was less pronounced under the CON system (data not shown).

The significant time effect on infiltration rate at the Brookings location exhibited a cyclic pattern through the growing season. For the no track position, infiltration rate increased during the year. At the row position and tracked position, infiltration rate was lowest at first sampling of the year, increased at the time of the second sampling, then decreased again. A similar, but less pronounced pattern occurred at the Mead location. For the Mead location, infiltration rate in the no track position was lowest at the first sampling of the year, then increased for the second sampling, and then decreased for the third sampling. Infiltration rate for the row and track positions increased during the growing season. At the Swift Current location, there was a general increasing infiltration rate during the course of each year (data not shown).

Table 2. Cropping system (CS) and time (T) effects on infiltration. Locations identified in bold type used the same tillage in the cropping system (other than no till).

Location	Position	CS	T	CS × T
Akron, CO	No track	*[1]	*	*
	Track	NS	*	NS
Brookings, SD	Row	NS	*	NS
	No track	NS	*	NS
	Track	NS	*	NS
Fargo, ND	Row	*	*	*
	No track	NS	*	NS
	Track	NS	NS	NS
Mandan, ND	Row	NS	NS	NS
	No track	*	*	*
Mead, NE	Row	NS	*	NS
	No track	NS	NS	NS
	Track	NS	*	NS
Sidney, MT	Row	NS	NS	NS
Swift Current, SK	No track	NS	NS	NS
	Track	NS	*	NS

[1] Significant treatment effects at $P = 0.05$ shown as * and NS indicates not significant.

Table 3. Infiltration rates (means of all dates) at each site and field-measurement position.

Location	Position	System	Mean	SD
			...... $cm\,h^{-1}$	
Akron, CO	No track	CON	17.9	2.6
		ALT	2.5	2.6
	Track	CON	1.6	0.3
		ALT	1.2	0.3
Brookings, SD	Row	CON	27.4	3.1
		ALT	19.9	3.1
	No track	CON	4.0	1.1
		ALT	2.6	1.1
	Track	CON	16.1	4.0
		ALT	15.0	4.0
Fargo, ND	Row	CON	110.0	15.6
		ALT	31.0	15.6
	No track	CON	129.0	36.4
		ALT	45.9	36.4
	Track	CON	26.3	10.9
		ALT	2.8	10.9
Mandan, ND	Row	CON	NE	NE
		ALT	NE	NE
	No track	CON	1.0	0.6
		ALT	5.0	0.6
	Track	CON	1.9	1.0
		ALT	3.9	1.0
Mead, NE	Row	CON	38.5	16.5
		ALT	77.3	16.7
	No track	CON	NE	NE
		ALT	NE	NE
	Track	CON	20.1	12.0
		ALT	28.1	11.4
Sidney, MT	Row	CON	16.1	3.8
		ALT	14.2	3.8
Swift Current, SK	No track	CON	10.8	3.1
		ALT	3.9	3.1
	Track	CON	4.2	1.1
		ALT	4.6	1.1

NE, the least square means of infiltration rate could not be estimated due to missing values.

Bulk density and water-filled pore space

Mean BD at each of the eight locations ranged from 0.9 $g\,cm^{-3}$ for the surface depth increment (0–7.5 cm) on native grassland to 1.6 g cm^{-3} for the lower depth increment (loam to sandy clay loam textures) at two locations. Typically, BD was greatest for cropped land as compared with native grassland (Table 4, grassland not shown). The greatest source of variation in BD was attributable to the time (T) of sampling (Table 5).

In tilled plots, there was a tendency for BD in the surface depth increment (0–7.5 cm) to increase during the growing season, probably as a result of soil reconsolidation after spring tillage operations. The tendency for soil reconsolidation is illustrated in Figure 1 for the Brookings site, where surface BD increased during the growing season and subsequently decreased at the beginning of the season except for the end of 2001 and in 2002 when tillage was suspended to permit the growth of alfalfa. Most changes in BD with time probably represent seasonal and annual variations generated by phases in the rotation, tillage and subsequent reconsolidation, and wetting–drying histories. For all locations, measured BD did not exhibit any obvious trend with GW (typical of soils having a low coefficient of linear extensibility). Moreover, there was no observable pattern in the error with which BD was estimated at each sampling time. Hence, we cannot recommend a single crop phase or time of the year at which BD should be measured to obtain the most reliable data for SQ assessments.

Differences in BD between cropping systems were most frequently observed at the soil surface depth increment (Table 5, five locations). For locations in which no-tillage was compared with CON tillage, tillage resulted in increased (Mandan), decreased (Fargo), or unchanged (Akron) BD near the surface. Soil texture and the time of tillage relative to sampling probably influenced how and the degree to which tillage influenced BD. Some BD in the lower depth increment of 15–30 cm approached threshold

Table 4. Dry aggregate size distribution (means of all dates) expressed as mean weight diameter (MWD) of surface soil (top 50 mm) and bulk density (BD) (0–75 mm and 75–150 mm) for conventional (CON) and alternative (ALT) cropping systems. Locations identified in bold type used the same tillage in the cropping system (other than no till).

	MWD		BD			
	Surface soil		0–75 mm		75–150 mm	
	CON	ALT	CON	ALT	CON	ALT
	mm		mg m^{-3}			
Akron			1.27	1.30	1.36	1.38
Brookings	8.32	8.41	1.36	1.35	1.54	1.54
Bushland	8.95	10.85	1.31	1.22	1.43	1.48
Fargo	8.04	10.63	1.00	1.17	1.12	1.22
Mandan	3.99	4.75	1.33	1.14	1.37	1.29
Mead	4.98	5.03	1.17	1.15	1.42	1.39
Sidney	NM	NM	1.44	1.51	1.54	1.52
Swift Current	21.86	22.69	1.23	1.23	1.38	1.42

NM, not measured.

Table 5. Analysis of variance dry aggregate size distribution expressed as mean weight diameter of surface soil (top 50 mm) and bulk density at 0–75 mm and 75–150 mm depths. Locations identified in bold-italic type used the same tillage in the cropping system (other than no till).

Effect	Akron	***Brookings***	Bushland	Fargo	Mandan	***Mead***	Sidney	***Swift Current***
				P-value, MWD of surface soil				
CS	NM	NS	0.051	0.016	NS	NS	NM	NS
T	NM	< 0.001	< 0.001	< 0.001	0.004	< 0.001	NM	0.001
CS × T	NM	0.056	0.083	NS	NS	< 0.001	NM	NS
				P-value, BD (0–75 mm)				
CS	NS	NS	0.014	0.005	0.004	0.018	0.012	NS
T	NS	< 0.001	< 0.001	NS	NS	< 0.001	0.013	NS
CS × T	NS	NS	0.039	NS	NS	NS	NS	NS
				P-value, BD (75–150 mm)				
CS	NS	NS	NS	NS	0.011	0.004	NS	NS
T	< 0.001	< 0.001	< 0.001	0.033	0.008	< 0.001	< 0.001	NS
CS × T	NS	NS	NS	NS	NS	NS	NS	NS

NM = not measured, T = time, significant treatment effects at $P = 0.05$, NS = not significant.

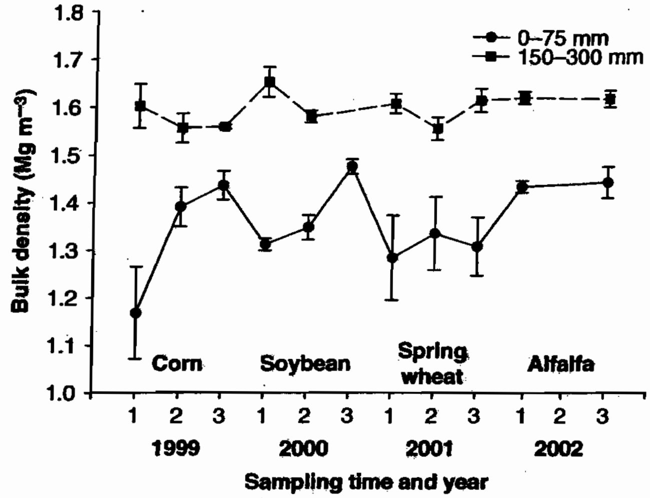

Figure 1. Bulk density throughout four seasons for the corn–soybean–spring wheat–alfalfa rotation (ALT) in Brookings, SD. Error bars represent ±1 SE.

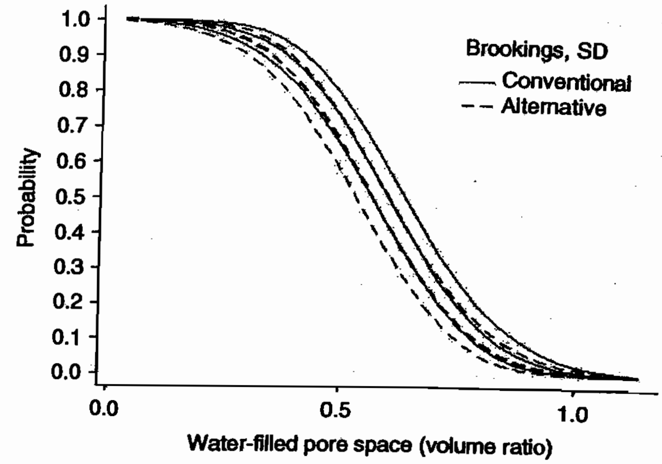

Figure 2. Normal probability function (and 95% confidence interval) of soil having a given volume ratio of water-filled pores (WFPS) within the top 300 mm at any time during the growing season of conventional (CON) and alternative (ALT) rotations at Brookings, SD. There was a 50% probability of achieving a WFPS of 0.6 under CON rotation and a 42% probability under ALT rotation.

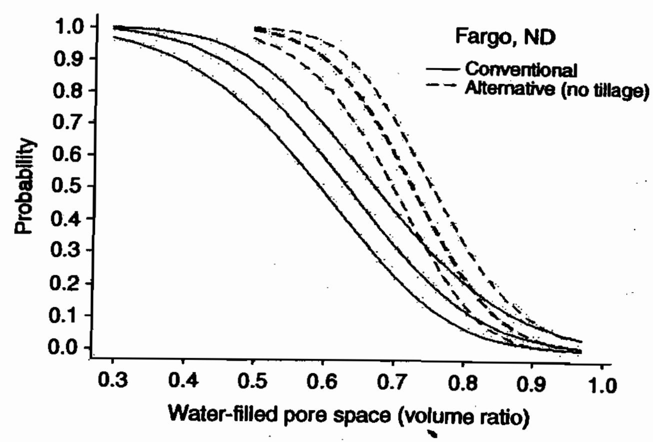

Figure 3. Normal probability function (and 95% confidence interval) of soil having a given volume ratio of water-filled pores (WFPS) within the top 300 mm at any time during the growing season of conventional (CON) and alternative (ALT) rotations at Fargo, ND. There was a 58% probability of achieving a WFPS of 0.6 under CON rotation and a 89% probability under ALT (no tillage) rotation.

densities restrictive to root growth[38]. For example, at Brookings, Mead, and Sidney, the average (cropping systems and dates) BD at 15–30 cm (data not shown) were 1.60, 1.44, and 1.56 g cm^{-3}.

Water-filled porosity, a function of BD and GW, fluctuated during the season and different rotational phases (data not shown). The greatest source of variation in these measurements was attributable to the time of sampling. Cropping systems containing a summer fallow period tended to have greater WFPS and GWs in the lower depth increments as compared to continuously cropped systems with similar tillage operations (Bushland and Swift Current). Comparisons between no tillage and conventionally tilled systems yielded mixed results (Mandan and Fargo).

We used a WFPS ratio of 0.6 as a SAT value[39] to delineate between water limiting and aeration limiting soil microbial processes. Doran et al.[40] have shown that aerobic microbial activity increases to a maximum at 0.6 and then decreases at higher values as aeration becomes limiting. Brookings, Fargo, and Mead had the highest occurrence (with time, treatment, or depth) of having WFPS values ⩾0.6 (there were 198, 117, and 225 measurements of WFPS taken during the study at Brookings, Fargo, and Mead, respectively).

Functions showing the probability of exceeding critical WFPS (with time, treatment, or depth) for Brookings and Fargo are shown in Figures 2 and 3, respectively. At Brookings, probability functions for CON and ALT management were not significantly (95% confidence interval) different. However, there was a 50% probability of exceeding SAT under CON management and a 42% probability of exceeding SAT under ALT management (Fig. 2). Management had a significant (95% confidence interval) effect on WFPS at Fargo (Fig. 3). There was a 58% probability of exceeding SAT under CON management and an 89% probability of exceeding SAT under ALT management.

No tillage was the ALT management at Fargo, and under 'cool and wet' soil conditions there was a greater probability of exceeding SAT under ALT, compared with CON management. At individual sites, precipitation history was the same for both ALT and CON, thus the comparison of WFPS between treatments reflects on only management. Therefore, the differences in soil water content between ALT and CON are a consequence of accelerated soil drying often associated with tillage operations.

Soil aggregates

Cropping system significantly affected MWD at Fargo and Bushland (Tables 4 and 5). Cropping systems at Fargo have a tillage variable where no tillage in the ALT treatment was compared with fall plow tillage in the CON treatment. Both systems at Bushland are under no tillage. MWD was greater under the ALT system at both Bushland and Fargo. Average (all dates) MWD at Bushland was 10.85 mm under ALT and 8.95 mm under CON (Table 4). Soil Microbial biomass C and N at Bushland was greatest under continuous wheat (ALT plots, 331 kg ha^{-1}) compared with a wheat–sorghum–fallow (CON plots, 209 kg ha^{-1}) rotation. This agrees with Liebig et al.[41] who found greater levels of glomalin, and wet aggregate stability under ALT management at Bushland. Mycorrhizal fungi are the source of glomalin and can improve soil structure (as suggested by greater wet aggregate stability and MWD under ALT management compared with CON) by forming water-stable soil aggregates[42].

A large MWD represents a DASD having a large portion of large aggregates. Data suggest that soil aggregates formed under no tillage (a system having elevated organic C) resist disintegration compared with aggregates under tillage. Studies at Brookings of a no tillage and CON tillage corn–soybean rotation (J.L. Pikul, unpublished data 2003) support the observation that dry aggregate stability is greater under no tillage compared with CON tillage. Bisal and Ferguson[43] showed that finer textured soils undergo tremendous changes with time over a multi-year weather cycle. Merrill et al.[44] found that the geometric mean diameter of aggregates on a silt loam soil increased from about 1–2 mm to about 20–30 mm with time. Average MWD for the Swift Current site (Table 4) was similar to that reported by Merrill et al.[44]

There was a significant effect of time on MWD at all locations (Table 5). At Brookings, MWD under ALT (4-year rotation) was significantly greater than CON (continuous corn) in the 4th year of the rotation (alfalfa phase). A similar comparison at Mead showed a smaller MWD under ALT compared with CON. MWD throughout three seasons are shown in Figure 4 for Brookings, SD and Figure 5 for Mead, NE. With the exception of the final measurements in 2002, there was not a statistically significant difference between treatments in MWD for either Brookings or Mead. The crop ending the 4-year rotation at Brookings is alfalfa and the improvement in aggregate stability (represented by a larger MWD value for ALT) may be a consequence of having a perennial like alfalfa in rotation.

MWD is a convenient way to generalize DASD, but expressing a distribution as a single number (e.g., MWD) fails to show differences in properties that influence aggregate stability. Chepil[33] proposed that dry aggregate stability could be measured by multiple passes through a rotary sieve, and we followed those ideas proposed by Chepil. We found differences in the distribution and stability of dry aggregates between treatments at Brookings and, to a lesser extent, treatments at Mead (Table 6).

Erodible fraction is defined as the percentage of soil mass <0.84 mm diameter, and this parameter has been related to soil wind erodibility. Merrill et al.[44] have shown that the erodible fraction was more sensitive to soil management effects than indices describing aggregate size distribution (e.g., MWD). The ALT treatment at Brookings had significantly greater fraction of large aggregates in groups 5 and 6 (Table 6) following the first sieving than did the CON treatment. As shown by the change in mass on second sieving, aggregates under ALT also had less tendency to abrade into small aggregates (groups 1 and 2) when

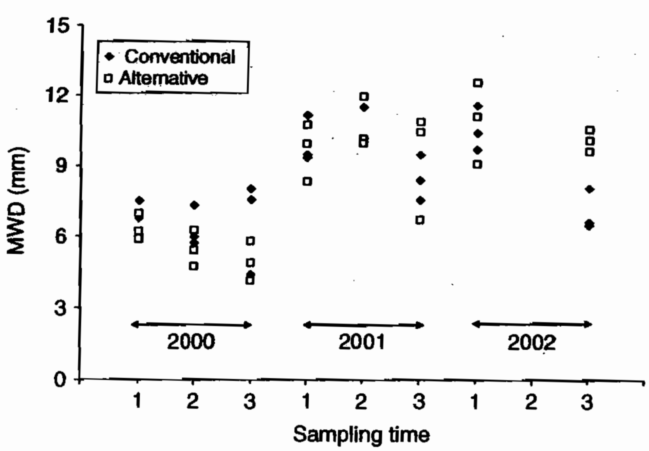

Figure 4. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Brookings, SD. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

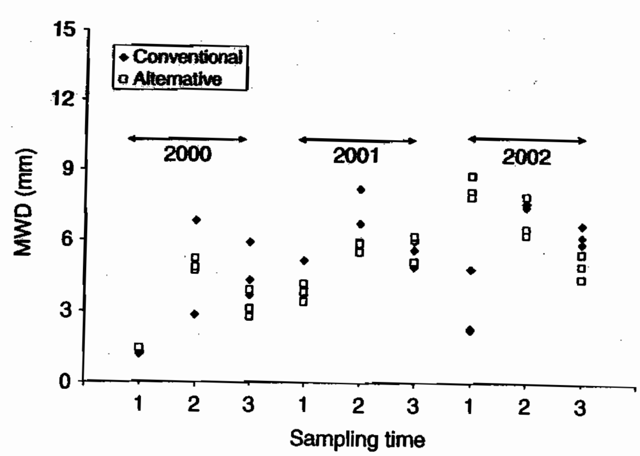

Figure 5. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Mead, NE. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

Table 6. Selected properties of soil aggregates for conventional (CON) and alternative (ALT) treatments at the Brookings and Mead sites. DASD, change in mass following second sieving (estimates dry aggregate stability), soil organic C, and water stability were measured on soil collected from the top 50 mm following harvest in 2002. A negative value indicates loss of soil (by abrasion) from that group. Group 1 was soil <0.4 mm, group 2 was 0.4–0.8 mm, group 3 was 0.8–2 mm, group 4 was 2–6 mm, group 5 was 6–19 mm, and group 6 was >19 mm.

	Aggregate group					
	1	2	3	4	5	6
Brookings						
DASD following 1st sieving ($g\,g^{-1}$)						
CON	0.20	0.10	0.12	0.15	0.20	0.23
ALT	0.07	0.05	0.10	0.16	0.23	0.39
P-value	0.004	0.003	0.055	NS	0.092	0.007
Change in mass following 2nd sieving ($g\,kg^{-1}$)						
CON	36.08	19.60	−0.27	−3.57	−14.80	−38.54
ALT	22.70	15.57	13.67	10.70	14.37	−78.22
P-value	0.040	NS	0.100	0.004	0.016	0.004
Soil organic C ($g\,kg^{-1}$)						
CON	16.23	18.92	18.81	19.33	17.68	18.49
ALT	16.99	20.49	22.53	20.35	17.76	17.71
P-value	NS	NS	0.033	NS	NS	NS
Water stability of dry aggregates (%)						
CON	NM	5.3	19.6	18.3	33.8	NM
ALT	NM	4.0	19.0	32.7	40.2	NM
P-value		NS	NS	0.099	NS	
Mead						
DASD following 1st sieving ($g\,g^{-1}$)						
CON	0.16	0.11	0.18	0.20	0.22	0.13
ALT	0.17	0.11	0.19	0.24	0.23	0.06
P-value	NS	NS	NS	0.083	NS	0.026
Change in mass following 2nd sieving ($g\,kg^{-1}$)						
CON	7.77	9.40	−4.87	−0.20	−2.83	−12.40
ALT	13.83	8.90	1.40	2.17	−11.57	−18.07
P-value	0.074	NS	NS	NS	NS	NS
Soil organic C ($g\,kg^{-1}$)						
CON	15.64	16.75	17.17	16.49	16.12	15.98
ALT	15.95	17.89	18.53	17.68	16.84	17.40
P-value	NS	NS	NS	NS	NS	NS
Water stability of dry aggregates (%)						
CON	NM	14.8	27.9	44.0	66.3	NM
ALT	NM	14.2	23.3	44.3	46.3	NM
P-value		NS	NS	NS	NS	

NM = not measured, significant treatment effects at $P = 0.05$ and NS = not significant.

compared with CON (Table 6, change in mass following second sieving). Aggregates in groups 1 and 2 are susceptible to wind erosion. We did not observe large differences between treatments at the Mead site following first or second sieving (Table 6).

Distribution of C among aggregate groups was not uniform. The ALT system had greater SOC than the CON system for both Brookings (except group 6) and Mead (Table 6). Dry aggregates from Brookings were less stable in water than those from Mead and this might be expected because the Brookings soil contains 466 $g\,kg^{-1}$ sand and 275 $g\,kg^{-1}$ clay. In contrast, the Mead soil contains 60 $g\,kg^{-1}$ sand and 380 $g\,kg^{-1}$ clay. Aggregates from groups 4 and 5 (Table 6) under ALT management at Brookings were significantly (Table 6, group 4, $P = 0.09$) more stable than those formed under CON. This was contrary to our findings for the Mead soil (Table 6, group 5), where the data suggest greater stability under CON compared with ALT (differences were not significant).

Characterizing surface conditions by quantifying both aggregate distribution and stability is important because the manner in which aggregates break down on sieving (dry aggregate stability) reveals an important physical trait that could be used as an attribute of soil quality (SQ). Within the same soil type, we think that aggregate stability is directly related to SOM status (J.L. Pikul, unpublished data 2005); however, we do not understand the temporal variation of this property within a system.

Values of MWD (calculated from aggregate distribution) provide a convenient way to show the dynamics of surface conditions with time as shown for Brookings (Fig. 4) and Mead (Fig. 5). Detailed analysis of aggregate properties, as conducted for the final soil samples (harvest 2002), at Brookings and Mead were laborious. Inspection of MWD values (Figs. 4 and 5) show that we conducted our detailed analysis of aggregates at a time when the MWD was close to an average value for the rotation cycle. For the Brookings site, MWD averaged across all dates was 8.3 mm for CON and 8.4 mm for ALT. Average MWD for the final sample was 7.0 mm for CON and 10.1 mm for ALT (Fig. 4). For the Mead site, MWD averaged across all dates was 5.0 mm for CON and 5.0 mm for ALT. Average MWD for the final sample was 6.2 mm for CON and 4.9 mm for ALT (Fig. 5).

DASD was expressed as MWD changes within a season and between seasons. Recognizing the temporal change in this surface soil property is important for understanding the dynamics of other soil properties linked to soil surface conditions such as water infiltration. Thus, MWD appears to be a useful trait for quantifying differences (at time of measurement) between management systems and as a measure to quantify temporal dynamics within a system.

Conclusions

Infiltration

Efficient water management requires attention to: (i) soil water use by crops (ii) reduction of water runoff, and (iii) opportunities to improve water recharge. Water intake rates are governed by surface and internal soil conditions and these conditions are ever-changing. Further, the inherently high spatial variability in water infiltration rates makes the interpretation of treatment effects difficult, especially in situations where tillage is used. We found no significant cropping system effects on infiltration for locations that had the same tillage system but differing cropping intensity or crop species in the cropping system. However, in the cases where no tillage was compared with tillage, infiltration was greater following tillage and declined over time in tilled systems. A cyclical pattern of infiltration rate was present for most cropping systems and locations, showing that a snap-shot of water infiltration (one-time measurement) would not be an appropriate SQ indicator because of significant temporal variation in infiltration rate. Measuring infiltration in wheel track and untracked parts of the field provides farmers with an understanding of how field operations affect this parameter and, in soils susceptible to reduced infiltration in traffic areas, will demonstrate the importance of controlling traffic patterns.

Bulk density and water-filled pore space

Long-term changes in BD indicative for use in SQ assessments would be difficult to establish and may be misleading if using a single sampling date, because BD changed significantly within each season and rotation. Multiple sampling dates throughout one or more rotational sequences are needed to ascertain long-term changes in BD.

Because most tillage operations on cropland are restricted to the upper 150 mm, and because soil root proliferation is typically greatest at shallow soil depths, BD measured near the surface was most sensitive to the effects of cropping systems. High BD (e.g., $>1.4\,g\,cm^{-3}$) near the surface, such as those observed at the Sidney location, are clearly undesirable. However, it may be difficult to ascertain if minor but significantly different BD observed at the surface for some of these treatment comparisons in fact lead to improved SQ. At lower soil depths, where BD more strongly influences root proliferation, a critical threshold criterion proposed by Arshad et al.[45] may be useful in evaluating these effects within an assessment framework for SQ. Tillage pans with narrow zones of high soil strength will also impede root proliferation. However, these features may sometimes be difficult to detect when the sampling depth increment is large.

WFPS, a function of BD and GW, fluctuated during the season and different rotational phases. We used a WFPS ratio of 0.6 as SAT value to delineate between water-limiting and aeration-limiting soil microbial processes. This approach provided a practical criterion for a systematic evaluation of distribution functions for the probability of exceeding a critical WFPS (with time, treatment, or depth). Systems having a high probability of exceeding SAT might then be viewed as having a detrimental effect on SQ. This criterion should be especially appropriate for locations having a combination of climate (cool and wet) and soil conditions (poorly drained) that pose a risk. For example, management at the Fargo location had a significant effect on WFPS and there was a high probability of exceeding SAT under no tillage when compared with tillage.

Identification of areas of a field having BDs exceeding threshold values for root elongation will be of interest to farmers. Management practices can be modified to address areas having high BDs due to activities such as wheel traffic or tillage. WFPS is an attribute that is more difficult to measure, but if areas of a field that exceed 0.6 WFPS for extensive periods of time can be identified, management practices such as improved drainage or reduced application of N fertilizer can be undertaken to lower the water content or decrease the potential for emission of greenhouse nitrogenous gases.

Soil aggregates

Greater MWD values were found under systems with greater cropping intensity and less tillage at Bushland and Fargo, respectively. A large MWD value represents an aggregate size distribution having a large portion of large aggregates. Our measurements suggest that DASD (expressed as MWD) may be a sensitive indicator of change in soil condition. Systems with a greater fraction of material that is erodible by wind (defined as material < 0.84 mm diameter) have a small MWD and consequently a detrimental effect on SQ (judged in respect to wind erosion). Further, measurements at two locations show that aggregates < 0.84 mm diameter contain a higher C concentration than bulk soil, and soil loss due to erosion would result in accelerated C loss from the system.

DASD, expressed as MWD, changed within a season and between seasons for reasons that we do not understand. Recognizing the temporal change in this surface soil property is important for understanding the dynamics of other soil properties linked to soil surface conditions such as water infiltration. Quantifying surface conditions by measuring MWD may be a convenient way to reference position in the time course of a rotation. Thus, MWD appears to be a useful trait for quantifying differences (at time of measurement) between management systems and as a way to plan detailed soil investigations within a temporally dynamic system.

Analysis of the change in mass of dry aggregate fractions (dry aggregate stability), following a second rotary sieving, also shows promise as a sensitive indicator of SQ. Soil aggregates that easily disintegrate to aggregate fractions < 0.84 mm are erodible by wind. Consequently, this measurement of SQ reveals an important link between a physical laboratory measurement and an important field characteristic of soil, that is, its susceptibility to wind erosion.

WFPS and soil aggregate properties show promise as diagnostic attributes of SQ. Within the constraints of our study, we found differences between treatments at some locations that encourage further testing. Probability that WFPS exceeds a threshold value could serve as a decision tool (related to SQ) for evaluating tillage practice within crop management systems. Tillage is often viewed as a destructive practice in respect to SOM because accelerated loss of soil C is associated with increased tillage intensity. However, tillage also promotes soil surface drying and increased soil temperature, and these properties are important to stand establishment in the colder and wetter soils of the northern Great Plains. Thus, there is a contradiction between resulting SQ attributes directly related to tillage.

In northern, sub-humid regions of the Great Plains, wind erosion takes place. Soil movement is less than in the southern Great Plains, but the consequences are the same. Fine soil particles lost to wind erosion are also the richest in organic matter. There may be opportunity to develop functions related to SQ for various crop and tillage management options based on the DASD and the quality of SOM within the various size fractions. Since the fine soil particles that are susceptible to loss via wind erosion contain a proportionately higher C, farmers should adopt practices that protect the soil from erosion. In the Great Plains, maintaining crop residue on the soil surface using conservation tillage is the most efficient practice for protecting the soil.

References

1 Campbell, C.A. and Souster, W. 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Canadian Journal of Soil Science 62:651–656.

2 Monreal, C.M. and Janzen, H.H. 1993. Soil organic-carbon dynamics after 80 years of cropping a Dark Brown Chernozem. Canadian Journal of Soil Science 73:133–136.

3 Rasmussen, P.E. and Parton, W.J. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. Soil Science Society of America Journal 58:523–530.

4 Biederbeck, V.O., Campbell, C.A., and Zentner, R.P. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. Canadian Journal of Soil Science 64:355–367.

5 Boyle, M., Frankenberger, W.T. Jr, and Stolzy, L.H. 1989. The influence of organic matter on soil aggregation and water infiltration. Journal of Production Agriculture 2:290–299.

6 Hudson, B.D. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49:189–194.

7 Bauer, A. and Black, A.L. 1992. Organic carbon concentration effects on available water capacity of three soil textural groups. Soil Science Society of America Journal 56:248–254.

8 Soane, B.D. 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil and Tillage Research 16:179–201.

9 Doran, J.W., Elliott, E.T., and Paustian, K. 1998. Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. Soil and Tillage Research 49:3–18.

10 Degens, B.P. 1997. Macro-aggregation of soils by biological bonding and binding mechanisms and the factors affecting these: a review. Australian Journal of Soil Research 35:431–459.

11 Mbagwu, J.S.C. and Bazzoffi, P. 1989. Properties of soil aggregates as influenced by tillage practices. Soil Use and Management 5:180–188.

12 Bruce, R.R., Langdale, G.W., West, L.T., and Miller, W.P. 1992. Soil surface modification by biomass inputs affecting rainfall infiltration. Soil Science Society of America Journal 56:1614–1620.

13 Pikul, J.L. Jr, Ramig, R.E., and Wilkins, D.E. 1993. Soil properties and crop yield among four tillage systems in a wheat–pea rotation. Soil and Tillage Research 26:151–162.

14 Pikul, J.L. Jr and Zuzel, J.F. 1994. Soil crusting and water infiltration affected by long-term tillage and residue management. Soil Science Society of America Journal 58:1524–1530.

15 Mulla, D.J., Huyck, L.M., and Reganold, J.P. 1992. Temporal variation in aggregate stability on conventional and alternative farms. Soil Science Society of America Journal 56:1620–1624.

16 Jones, O.R., Hauser, V.L., and Popham, T.W. 1994. No-tillage effects on infiltration, runoff, and water conservation on

dryland. Transactions of the American Society of Agricultural Engineers 37:473–479.

17 Pikul, J.L. Jr and Aase J.K. 2003. Water infiltration and storage affected by subsoiling and subsequent tillage. Soil Science Society of America Journal 67:859–866.

18 Seta, A.K., Blevins, R.L., Frye, W.W., and Barfield, B.J. 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. Journal of Environmental Quality 22:661–665.

19 Edwards, W.M., Triplett, G.B., Van Doren, D.M., Owens, L.B., Redmond, C.E., and Dick, W.A. 1993. Tillage studies with a corn–soybean rotation: Hydrology and sediment loss. Soil Science Society of America Journal 57:1051–1055.

20 Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Science 119:242–249.

21 Rhoton, F.E., Bruce, R.R., Buehring, N.W., Elkins, G.B., Langdale, C.W., and Tyler, D.D. 1993. Chemical and physical characteristics of four soil types under conventional and no-tillage systems. Soil and Tillage Research 28:51–61.

22 Vyn, T.J. and Raimbault, B.A. 1993. Long-term effect of five tillage systems on corn response and soil structure. Agronomy Journal 85:1074–1079.

23 Bruce, R.R., Langdale, G.W., and Dillard, A.L. 1990. Tillage and crop rotation effect on characteristics of a sandy surface soil. Soil Science Society of America Journal 54:1744–1747.

24 Blevins, R.L., Smith, M.S., Thomas, G.W., and Frye, W.W. 1983. Influence of conservation tillage on soil properties. Journal of Soil and Water Conservation 38:301–305.

25 Chang, C. and Lindwall, C.W. 1990. Comparison of the effect of long-term tillage and crop rotation on physical properties of a soil. Canadian Agricultural Engineering 32:53–55.

26 Mielke, L.N., Wilhelm, W.W., Richards, K.A., and Fenster, C.R. 1984. Soil physical characteristics of reduced tillage in a wheat–fallow system. Transaction of the American Society of Agricultural Engineers 27:1724–1728.

27 Allmaras, R.R., Pikul, J.L. Jr, Kraft, J.M., and Wilkins, D.E. 1988. A method for measuring incorporated crop residue and associated soil properties. Soil Science Society of America Journal 52:1128–1133.

28 Pikul, J.L. Jr and Allmaras, R.R. 1986. Physical and chemical properties of a Haploxeroll after fifty years of residue management. Soil Science Society of America Journal 50:214–219.

29 Varvel, G., Reidell, W., Deibert, E., McConkey, B., Tanaka, D., Vigil, M., and Schwartz, R. 2006. Great Plains cropping system studies for soil quality assessment. Renewable Agriculture and Food Systems 21:3–14.

30 Gardner, W.H. 1986. Water content. In A. Klute (ed.). Methods of Soil Analysis Part 1: Physical and Mineralogical Methods. 2nd ed. American Society of Agronomy, Madison, WI. p. 493–544.

31 Blake, G.R. and Hartge, K.H. 1986. Bulk density. In A. Klute (ed.). Methods of Soil Analysis Part 1: Physical and Mineralogical Methods. 2nd ed. American Society of Agronomy, Madison, WI. p. 363–375.

32 Hillel, D. 1971. Soil and Water Physical Principles and Processes. Academic Press, New York, NY.

33 Chepil, W.S. 1962. A compact rotary sieve and the importance of dry sieving in physical soil analysis. Soil Science Society of American Proceedings 26:4–6.

34 Kemper, W.D. and Rosenau, R.C. 1986. Aggregate stability and size distribution. In A. Klute (ed.). Methods of Soil Analysis Part 1: Physical and Mineralogical Methods. Agronomy Monograph No. 9, 2nd ed. American Society of America, Madison, WI. p. 425–444.

35 Chepil, W.S. 1951. Properties of soil which influence wind erosion: IV. State of dry aggregate structure. Soil Science 72:387–401.

36 Lowery, B., Hickey, W.J., Arshad, M.A., and Lal, R. 1996. Soil water parameters and soil quality. In J.W. Doran and A.J. Jones (eds). Methods for Assessing Soil Quality. Soil Science Society of America Special Publication no. 49. Soil Science Society of America, Madison, WI. p. 143–155.

37 Littell, R.C., Milliken, G.A., Stroup, W.W., and Wolfinger, R.D. 1996. SAS System for Mixed Models. SAS Institute Inc., Cary, NC, USA.

38 Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Science Society of America Journal 47:1208–1211.

39 Parkin, T.B., Doran, J.W., and Franco-Vizcaino, E. 1996. Field and laboratory tests of soil respiration. In J.W. Doran and A.J. Jones (eds). Methods for Assessing Soil Quality. Soil Science Society of America Special Publication, no. 49. Soil Science Society of America, Madison, WI. p. 231–245.

40 Doran, J.W., Mielke, L.N., and Power, J.F. 1990. Microbial activity as regulated by soil water-filled pore space. In Transactions of the 14th International Congress of Soil Science, Kyoto, Japan, 12–18 August. International Society of Soil Science, Wageningen, The Netherlands. p. 94–100.

41 Liebig, M., Carpenter-Boggs, L., Johnson, J.M.F., Wright, S., and Barbour, N. 2006. Cropping system effects on soil biological characteristics in the Great Plains. Renewable Agriculture and Food Systems 21:36–48.

42 Wright, S.F. and Upadhyaya, A. 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. Plant and Soil 198:97–107.

43 Bisal, F. and Ferguson, W.S. 1968. Monthly and yearly changes in aggregate size of surface soils. Canadian Journal of Soil Science 48:159–164.

44 Merrill, S.D., Black, A.L., Fryrear, D.W., Saleh, A., Zobeck, T.M., Halvorson, A.D., and Tanaka, D.L. 1999. Soil wind erosion hazard of spring wheat–fallow as affected by long-term climate and tillage. Soil Science Society of America Journal 63:1768–1777.

45 Arshad, M.A., Lowery, B., and Grossman, B. 1996. Physical tests for monitoring soil quality. In J.W. Doran and A.J. Jones (eds). Soil Science Society of America Special Publication, no. 49. Soil Science Society of America, Madison, WI. p. 123–142.